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The performance of beer packaging : vibration damping and thermal insulation

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“The performance of beer packaging: vibration damping and thermal insulation”

ABSTRACT

Poor transport conditions can result in an accelerated decay in beer quality. Optimal beer packaging should minimize the impact of temperature changes and vibrations, which occur during (long-haul) transport. In this research, the performance of different beer packagings (BP) regarding vibration damping and thermal insulation was investigated. Three BP's were tested (A: 24x33cl cardboard crate / B: 6x25cl cardboard crate + plastic foil / C: 24x25cl plastic crate).

Cardboard in combination with plastic foil (BP- B) appears to be the best packaging strategy due to the positive thermal insulation properties of cardboard. The plastic foil ties the beer bottles together leaving little space for the bottles to move and therefore reduces the air transfer contributing to better thermal insulation properties. Finally, cardboard in combination with plastic foil exhibits damping characteristics. With a holistic BP strategy, one can control vibrations and temperature biases, which is beneficial for the quality of beer.

Highlights

- Cardboard with plastic foil (BP-B) has the best packaging performance in this study
- Cardboard has positive thermal insulation properties
- Plastic foil reduces bottle movement (vibrations) and air transfer (temperature)
- Cardboard in combination with plastic foil exhibits damping characteristics

Keywords

Beer packaging, vibrations, temperature, packaging strategy

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FIGURE Graphical Table of Contents (GTOC)

“The performance of beer packaging: vibration damping and thermal insulation”

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1. INTRODUCTION

In recent years European beer exports have significantly increased, growing to 78 million hL in 2012 (Brewers of Europe, 2015). Market globalization has induced higher beer production and export volumes. As a result, beer is increasingly more exposed to longer transportation times and variable storage conditions. These transport and storage conditions lead to chemical reactions that cause changes in the chemical composition of beer (Vanderhaegen, Neven, Verachtert, & Derdelinckx, 2006). Chemical reactions, mostly initiated by oxidative reactions, generate chemical compounds that alter the sensorial properties of beer (Jaskula-Goiris, De Causmaecker, De Rouck, De Cooman, & Aerts, 2011; Malfliet et al., 2008). While aging with respect to wines is sometimes perceived as desirable since it enhances certain flavours and aromas, beer ageing results in undesirable flavour changes. As a consequence, the flavour quality and stability of beer change over time. An increase of aldehydes, a decrease in bitterness compounds (iso- α -acids), permanent haze and change of colour are some of the effects related to beer ageing. Ageing characteristics differ between beer types, however, in general, an increase in sweet aromas and a decrease of bitter tastes are mostly observed (Baert, De Clippeleer, Hughes, De Cooman, & Aerts, 2012; Malfliet et al., 2008; Vanderhaegen, et al., 2006). Shelf-life problems due to flavour instability have become an important issue to breweries. In order to meet the expectations of the consumer beer should have a constant uniform flavour. When beer has aged and the flavour and aroma diverges from fresh beer, the latter may result in a rejection of the beer brand by the consumer and decreasing sales (Vanderhaegen, et al., 2006).

1.1 Beer packaging

A dedicated packaging strategy is essential to maintain a high quality and stable beer flavour. Beer is predominantly stored in kegs, glass bottles, aluminum cans, and PET-bottles (Donoghue, Jackson, Koop, & Heuven, 2012). Since consumer expectations and preferences differ, the type of packaging varies significantly between countries. European countries, for example, use primarily glass bottles, while the consumers in the USA prefer the use of aluminum cans. Marketability and product appeal are important factors when determining the packaging strategy. In recent years, efforts of countries were intensified to reduce the environmental impact of the packaging. As a consequence, also the regional legislation regarding packaging taxes and deposit systems influences the packaging decision. The packaging materials used by the European breweries (in 2010) are:

- 1) Glass bottles (44.2%), of which returnable (24.5%) and non-returnable (19.7%)
- 2) Metal cans (24.7%)
- 3) Kegs (20.7%)
- 4) PET bottles (6.8%), of which returnable (0.7%) and non-returnable (6.1%)
- 5) Bulk beer tanks (2.8%)
- 6) Others (0.8%)

Source: (Donoghue et al., 2012)

The use of the different beer containers can also be segmented by transportation distance. Due to its recycling logistics, kegs are mostly not transported to foreign countries with long transportation distances. Therefore, beer in kegs is predominantly used for domestic consumption. Bottles and metal cans, on the other hand, are used domestically and also exported to foreign countries. Non-returnable glass bottles or 'single-use' bottles are mainly

used for export. Returnable or reusable glass bottles are heavier to make them more durable as each bottle can be used multiple times in a recycling process. A secondary packaging is used to transport bottles and metal cans. Glass bottles used for domestic consumption are mostly transported in hard plastic crates to accommodate the recycling logistics. When exporting to other countries, bottles and cans are packaged using cardboard (cardboard crate or holder) and plastic foil (not required when using a cardboard crate). (Donoghue et al., 2012; Euromonitor International, 2014)

1.3 Parameters influencing beer quality

Research of Burns, Heyerick, De Keukeleire, & Forbes (2001) and Jaskula-Goiris et al. (2011) indicated that exposure to light and temperature influence the amount of chemical ageing reactions occurring in beer. Until recently, breweries focused on minimizing the exposure to light and temperature changes in order to maintain the quality of beer when choosing their packaging strategy. However, by limiting the mass and the materials used in the packaging also economic and ecological considerations are incorporated in the packaging decision process. The optimal temperature of beer storage suggested in literature is fixed between 0 and 5 °C. The freshness of beer decreases with higher temperatures, lowering the reaction activation energy and thereby increasing the amount of chemical reactions that take place. Furthermore, every reaction type has a different level of activation energy, which implies that reaction rates are different with increasing temperature. As a result, with increasing temperature different chemical compounds of different reactions are formed in an unequal volume (Jaskula-Goiris et al., 2011). Quality deterioration of beer can also be caused by an exposure to light, a phenomenon referred to as ‘lightstruck flavor’. This can be attributed to the absorption of energy, generating an intramolecular energy transfer which causes several chemical reactions (Burns et al., 2001). The vulnerability of iso- α -acids to light can be indicated as the main contributor to photodegradation of beer or its ‘lightstruck flavor’. In order to prevent light-induced deterioration, breweries store their beers in light-proof containers (e.g. colored bottles or cans) (Caballero, Blanco, & Porras, 2012).

During transport, beer is also exposed to vibrations and shocks. In rare experiments (Janssen, et al., 2014) it was found that vibrations could have an influence on the quality of a food product. Moreover, the authors signaled the emergence of turbidity in beer caused by vibrations. However, limited research has been done on the impact of vibrations on the chemical and sensorial quality of beer. Oxidative reactions initiate a range of different chemical reactions that result in beer ageing. As a consequence, breweries tend to avoid a high level of oxygen when producing and bottling beer. In recent years, the oxygen in beer can be reduced to 0,1mg/l with modern filling techniques (Caballero, et al., 2012). When beer is exposed to vibrations, the oxygen in the upper part of the bottle under the crown will be mixed with the beer. This will enable the beer to have more oxidative reactions and thereby accelerate the beer ageing process. Furthermore, vibrations could increase the collision of molecules, which will lower the reaction activation energy. As a consequence, the generation of ageing compounds will be facilitated. Hence, one can conclude that vibrations can be harmful to the beer quality, and should therefore be avoided.

Beer is commonly transported using trucks, trains, and ships. Depending on the transport carrier, beer is exposed to different vibrations and shocks. Vibrations are periodic in nature while a shock is a single-event or transient phenomenon (Harris, & Piersol, 2002). Vibrations

generated by a truck, for example, are influenced by the road conditions (roughness), the driving performance (traveling speed) and the specifications of the truck (load, suspension, the number of axles, etc.) (Garcia-Romeu-Martinez, Singh & Cloquell-Ballester, 2008; Jarimopas, Singh, & Saengnil, 2005; Lu, Ishikawa, Kitazawa, & Satake, 2010). Furthermore, the position inside a container has an influence on the amplitude of the vibrations (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2003; Zhou, Su, Yan, & Li, 2007). The vibration spectrum of trucks, trains and ships are characterized in the academic literature (mostly an averaged spectrum to characterize multiple transport vehicles) (Maheras, Lahti, & Ross, 2013). Most of the vibrations of these transport vehicles occur in the frequency range below 100 Hz with accelerations smaller than 10 m/s^2 . Based on these findings, boundaries in frequency and acceleration were defined in the experimental design presented in section 2.1.

1.4 Paper structure and flow

The aim of the current work is twofold: (1) to identify the vibration damping performance of three beer packaging strategies that are commonly used in industry, and (2) to look into the thermal conductivity of the beer packaging. During transport, beer is exposed to vibrations with amplified or attenuated magnitude due the vibration transmissibility performance of the beer packaging. Different packaging strategies have different transmissibility curves and vibration damping performance, making it able to compare and benchmark them. The second objective was to look into the thermal conductivity or thermal insulation of the beer packaging. Increasingly breweries export beer in cooled containers to counteract the influence of temperature on the beer flavor. However, thereafter in next steps in the supply chain, the temperature may rise and can be as high as 50°C (Weiskircher, 2008). With an experimental set-up, the insulating performance of the beer packaging was tested. To summarize, the objective is to identify the performance of three commonly used beer packaging strategies regarding thermal insulation and vibration damping.

The research performed in current paper can be generalized for other food and beverage products. Diverse academic papers focus on the impact of shocks on the mechanical damage of fresh products (apples, kiwis, tangerines, etc.) (Jarimopas et al., 2005; Tabatabaekolour, Hashemi, Taghizade, 2013; Van Zeebroeck et al., 2008). Other research papers (Berardinelli et al., 2003; La Scalia et al., 2015) investigate the influence of vibrations on the microbial growth and change of chemical components of highly perishable products (strawberries, eggs etc.). Besides, the effects of temperature during transport and storage on food and beverage quality (wine, tomatoes, etc.) has been extensively investigated (Butzke, Vogt, & Chacón-Rodríguez, 2012; Tano, Oulé, Doyon, Lencki, & Arul, 2007). Similar to the study of Eissa, Gamaa, Gomaa, & Azam (2012) this study also evaluates the effect of vibrations on products and their packaging materials, without exploring the modal parameters but rather the transmissibility of vibrations (Eissa et al., 2012). Furthermore, this study focuses on the packaging of beer and adds further insights to literature by also translating vibration and thermal performance into an alternative and recommended packaging strategy.

The remainder of the paper is structured as follows: In Section 2 ‘Methodology and experimental set-up’ the context and definitions of the study and the design of the experiments are described. In Section 3 the results of the experiments are presented. Moreover, the focus is on how to interpret the research findings and translate them into an

improved beer packaging strategy. In Section 4 the conclusions of the paper are presented, highlighting key results and limitations of the study.

2. METHODOLOGY AND EXPERIMENTAL – SETUP

2.1 Vibrations

From a theoretical point of view, an estimate of the resonant frequencies of the beer packaging can be calculated using the Rayleigh-Ritz method (Harris, & Piersol, 2002). However, this estimation is complex due to the fact that information is required about the properties of the materials (stiffness coefficients), the geometrical shape of the bottles and the impact of beer bottles interacting with each other. However, an alternative approach in which practical insights can be formulated based on actual data, is to execute an experiment and to calculate the transmissibility function. The acceleration transmissibility function is defined as the function that can be calculated by dividing the Fourier transform of the measured accelerations of the highest accelerometer by the Fourier transform of the accelerations measured on the lowest accelerometer.

For the purpose of this experiment, an electro-dynamic shaker (Brüel & Kjær, type 4802T) was used to generate vibrations. Literature states that the lateral and longitudinal vibration levels are extremely low compared to the vertical vibration levels during truck transport (Garcia-Romeu-Martinez et al., 2008). Therefore, in this experiment vibrations were applied in a single dimension, i.e. vertical relative to the surface area. The vibration table generated a sine sweep rate of vibrations starting at 2 Hz and ending at 100 Hz with an acceleration level of approximately 1 G (duration 200 seconds). The objective was to artificially replicate vibrations at frequencies and acceleration levels that appear during truck transport.

A first accelerometer was mounted on the base plate, measuring acceleration in the vertical direction. In order to not limit the movement of the bottle and influence the interaction between the bottle and the packaging, a second accelerometer was mounted on the beer bottleneck (also in the vertical direction). Both accelerometers had a sample rate of 100k samples/sec. The ‘Nyquist frequency’ is required to be at least higher than 100 Hz to counteract the aliasing effect (Harris, & Piersol, 2002). With the acceleration data of both accelerometers a transmissibility function was calculated.

Three different types of beer packagings A, B, and C were tested:

A: 24 bottles of 33cl in cardboard crate – Longneck (green) – mass bottle: 553 g – mass packaging: 14.76 kg [Figure 1: picture 1]

B: 4 packages with 6 bottles of 25cl in cardboard crate with plastic foil per 6 bottles – Vichy (brown) – mass bottle: 494 g – mass: 11.86 kg [Figure 1: picture 2]

C: 24 bottles of 25cl hard plastic crate – Vichy (brown) – mass bottle: 494 g – mass: 16.96 kg [Figure 1: picture 3]

Packagings A and B are frequently used in international transports and packaging C is mainly used in domestic transports. Due to the scope of the project and the stakeholders involved, the three beer packages, including bottle types, were selected for being most commonly used by Belgian breweries. Although packagings A, B and C are a packaging standard in industry, breweries might add minor changes to their packaging by altering the basic components (cardboard, plastic foil and hard plastic). The findings in this research are a starting point for future research enabling the benchmarking of alternative packaging strategies.

First, a vibration test was performed with no extra load on the bottom plate (without a beer packaging). Afterwards, vibration tests were performed on the three packagings that were

strapped on the shaker plate. The amplitude of the shaker was adapted as a function of the mass of the packaged beer to make sure that an acceleration level of approximately 10 m/s^2 was imposed on the base plate.

The data generated by the two transducers have been analyzed using Matlab R2015a. After plotting the two time series a Fourier transform (bandwidth / frequency resolution 1 Hz) was performed. Finally, an estimation of the transmissibility function from the shaker plate to the beer bottleneck was calculated. A low bandpass filter was applied with a moving average filter with a filter length of 10 samples to attenuate the 50 Hz noise component resulting from the shaker.

Figure 1: Experimental set-up [vibration damping – packaging performance]

2.2 Temperature

Brewers want to provide customers with beer of the best possible quality. However, when refrigerated containers reach storage after being transported, the temperature can promptly rise. For the purpose of this research, the container temperature of a ship transport from Antwerp (Belgium) to Tokio (Japan) was monitored (Figure 2). Figure 2 shows that a constant low temperature (3°C) was measured during transport. After transportation a different temperature regime is present, since temperature rose sharply after arrival in its storage facility (27°C).

Figure 2: Container temperature of a ship transport from Belgium to Japan during summer

In literature, evidence was reported on containers heating up to temperatures up to 50 °C under direct sunlight (Weiskircher, 2008). These findings were used as a starting point when designing and benchmarking the temperature experiment discussed in this section. Since high temperature is harmful to the beer quality, the beer packaging should protect the beer against a rising temperature. In other words, beer packaging with low thermal conductivity or high thermal insulation properties are preferred.

In order to simulate the heating up of a container, an experiment was performed. In this experimental set-up (Figure 3), the same beer packagings A, B and C as in the vibration experiment (section 2.1) were tested. First, the beer packagings were stored in a cold storage room with a temperature of 5 °C (in still air). Once the beer had reached the ambient temperature of the environment, the beer packagings were transferred to heating chambers with a temperature of 30 °C and 40 °C (in still air). The objective of the study is to determine the thermal properties of different types of beer packaging in order to protect beer from a higher ambient temperature of 30 °C (respectively 40 °C). The temperature was measured in the fluid using a logger of the brand 'PCsensor', doing a measurement every second. In this experiment beer was substituted by water, because with rising temperature, beer would start foaming. This study focusses on the thermal insulation properties of beer packaging and since beer consists of 90% water (Donoghue et al., 2012), this substitution is acceptable. A small incision in the packaging was made to put the cable connection with the computer, and was afterwards tightly closed with plastic. An exponential function best represented the raw data and, therefore, was fitted to the raw signals.

Figure 3: Experimental set-up [thermal insulation – packaging performance]

3. RESULTS & DISCUSSION

3.1 Vibrations

The amplitude of the acceleration transmissibility function of packagings A and B is displayed in respectively Figures 4 and 5. The plot represents the frequency (Hz) and the acceleration transmissibility factor (the division of the Fourier transform of the measured accelerations on the beer bottle by the Fourier transform of the accelerations measured on the shaker plate). When the magnitude of the curve is above one (red line), vibrations of a specific frequency are amplified. A magnitude between zero and one indicates that the vibrations of a specific frequency are attenuated by the packaging. The packaging of the beer will tend to behave as a vibration damper.

Figure 4: Transmissibility Package A

(Sweep rate from 2 to 100 Hz, acceleration of 10 m/s² over 200s)

Figure 5: Transmissibility Package B

(Sweep rate from 2 to 100 Hz, acceleration of 10 m/s² over 200s)

Figure 6: Transmissibility Package C

(Sweep rate from 2 to 100 Hz, acceleration of 20 m/s² over 200s)

The transmissibility functions of beer packaging A and B presented in Figures 4 and 5 show a completely different transmission behavior. Packaging A transmits vibrations from 2 to 70 Hz while at higher frequencies vibrations are amplified by the beer packaging. From 70 to 100 Hz the increase is exponential up to an acceleration transmissibility factor of four. This particular shape of the curve was similar to the research findings on corrugated cardboard in

the academic literature (Huang, 2013). This suggests that with respect to the transmissibility the secondary beer packaging (cardboard crate) of packaging A is of higher significance than other parameters e.g. the particular bottle shape. As a consequence, packaging A underperforms compared to packaging B. Packaging B tends to be a good vibration damper for vibrations higher than 60 Hz. High-frequency vibrations will decrease in magnitude by 50% caused by the packaging material. A possible explanation could be that plastic foil is a decent vibration damper with performance characteristics similar to rubber (Harris, & Piersol, 2002).

The transmissibility function of packaging C (Figure 6) has a magnitude close to one for the whole spectrum. However, the graph should be interpreted with caution because its particular shape is influenced by a ‘feedback effect’. The shaker imposes vibrations on the shaker plate (input accelerometer) and subsequently the beer packaging. Since the beer bottles in packaging C, a standard hard plastic crate used for domestic transports, have free space to move within the packaging, the bottles also generate vibrations. These vibrations are measured again by the accelerometer on the shaker plate. The impact of a beer bottle jumping up and down in the crate generates abundant noise in the frequency spectrum. The effect is similar to imposing a shock. When analyzing the time domain plot (Figure 7), the amplitude level of packaging C is noteworthy. In this particular case, a sweep rate from 2 to 100 Hz is exposed with acceleration level of 20 m/s^2 . At a frequency level of approximately 7 to 13 Hz beer bottles start ‘jumping’. When imposing the same sweep rate on packaging A (Figure 8), a similar image can be found. Bottles start bumping into each other at frequencies between approximately 7 to 13 Hz and 19 to 23 Hz. When imposing sweeps with lower acceleration the phenomenon of bottles bumping into each other cannot be found for packaging A. From this analysis we can conclude that in order to limit the vibrations, the bottles in packaging A should be foreseen with panels separating the bottles from each other. In packaging B, the bottles are packed close to each other what makes it more difficult for the bottles to move individually.

Figure 7: Time domain plot Package C

(Sweep rate from 2 to 100 Hz, acceleration of 20 m/s^2 over 200s)

(X-axis represents time or number of samples but is related to the frequency in the sweep)

Figure 8: Time domain plot Package A

(Sweep rate from 2 to 100 Hz, acceleration of 20 m/s^2 over 200s)

(X-axis represents time or number of samples but is related to the frequency in the sweep)

The stiffness and damping coefficient, in the literature defined as the effect of a spring damper system, characterize the vibration damping properties of the beer packaging. However, in reality, multiple packages are stacked upon each other, making the system more

complex. Moreover, the mass will be different, there is an effect of multiple layers of products and their packaging materials, the way of stacking will have influence on the vibration characteristics etc. Furthermore, the highest stacked packages will have a larger moment increasing the amplitude of vibrations and shocks, in the case of truck and train transport. Academic literature reports the acceleration of vertical vibrations of the highest stacked boxes of transported peaches to be three to four times higher than those of the lower stacked boxes (O'Brien, Gentry, & Gibson, 1965).

3.2 Temperature

In practice, beer packages are stacked close to each other, slowing down the beer heating process. In a similar manner, cold beer bottles closely packed together prevent each other from heating up. Furthermore, the packaging material can act as a thermal insulator. The use of plastic can control the airflow, leaving cold air inside and warm air outside. Corrugated cardboard can be characterized as a good thermal insulator, caused by the air in the pores of the material.

Figure 9: Results beer temperature (30°C) **Figure 10: Results beer temperature (40°C)**
(Experiment: Thermal insulation of the beer packaging; beer temperature reaching the ambient temperature of 30°C / 40°C)

In Figures 9 and 10, the thermal insulation performance of packagings A, B and C can be found. Packaging A has the best insulation properties, however, the curves of beer packagings A and B behave in a similar manner. In packaging A, the cardboard crate, no air movement is possible because the opening on top is covered with plastic tape. Packaging B, the cardboard crate covered in plastic foil, has little air transfer from the sides of the beer packaging. In beer packaging C, the hard plastic crate, bottles are open to the environment hence heating up more rapidly. The temperature of beer bottles in packaging C reaches the ambient temperature after 5 hours, whereas the bottles of packagings A and B only reach the same level after 24 hours.

4. CONCLUSIONS

The packaging of beer has an influence on the exposure of beer to temperature differences and vibrations. All elements need to be taken into account to regulate the shelf life of beer regarding flavor stability. Within the current work different beer packaging types A, B and C are benchmarked with regard to vibrations and temperature.

Packaging B tends to perform best in damping vibrations. The beer packaging attenuates vibrations higher than 60 Hz. Beer packaging A resonates at frequencies higher than 80 Hz and therefore performs weakly. Packaging C performs worst regarding damping of vibrations: beer bottles have free space to move within the beer packaging, which results in an (uncontrollable) amplification of the vibrations. Furthermore, the time domain plots (Figures 7 and 8) indicate that when bottles are free to move critical resonance frequency areas can be pinpointed from 7 to 13 Hz, and from 19 to 23 Hz. Packaging C, and to a lesser extent packaging A, are sensitive for vibrations within the latter mentioned frequency ranges (and at a considerably high acceleration).

Regarding thermal insulation, beer packagings A and B perform relatively similar. Furthermore, beers from packagings A and B have significantly better thermal insulation properties than beers of packaging C. The use of cardboard, which is an adequate insulator material, combined with plastic tape or foil to reduce the air movement, is the best packaging strategy (of the three used in the study) in terms of thermal insulation.

To conclude, the use of cardboard in combination with plastic foil (packaging B) is the best beer packaging strategy regarding vibration damping and thermal insulation. Cardboard has positive thermal insulation properties. The plastic foil ties the beer bottles together into one solid mass leaving little space for the bottles to move. At the same time, the foil reduces the air movement contributing to better thermal insulation properties. Finally, the use of cardboard in combination with plastic foil shows interesting damping characteristics.

Little is known in literature about the impact of transport vibrations and the interaction with temperature on the chemical and sensorial quality of beer. In future research, this topic should be further investigated. A potential area of future research is to quantify the quality deterioration of beer caused by vibrations. Furthermore building on the latter, a better understanding is essential to detect whether high or low frequency vibrations are most harmful for the beer quality. If the vibrations amplified by the beer packaging (e.g. frequencies above 70 Hz for packaging A) correspond to the frequency ranges where the quality of beer significantly declines, an alternative packing strategy needs to be recommended. Alternative or additional packaging materials can be used to control vibrations.

5. REFERENCES

- Baert, J. J., De Clippeleer, J., Hughes, P. S., & De Cooman, Luc, Aerts, G. (2012). On the origin of free and bound staling aldehydes in beer. *Journal of Agricultural and Food Chemistry*, 60(46), 11449–72. <http://doi.org/10.1021/jf303670z>
- Berardinelli, A., Donati, V., Giunchi, A., Guarnieri, A., & Ragni, L. (2003). Effects of Transport Vibrations on Quality Indices of Shell Eggs. *Biosystems Engineering*, 86(4), 495–502. <http://doi.org/10.1016/j.biosystemseng.2003.08.017>
- Brewers of Europe. (2015). *Beer statistics – edition 2015 – period 2009-2014*. Retrieved from http://www.brewersofeurope.org/site/media-centre/index.php?doc_id=840&class_id=31&detail=true
- Burns, C. S., Heyerick, A., De Keukeleire, D., & Forbes, M. D. (2001). Mechanism for formation of the lightstruck flavor in beer revealed by time-resolved electron paramagnetic resonance. *Chemistry (Weinheim an Der Bergstrasse, Germany)*, 7(21), 4553–61. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11757646>
- Butzke, C. E., Vogt, E. E., & Chacón-Rodríguez, L. (2012). Effects of heat exposure on wine quality during transport and storage. *Journal of Wine Research*, 23(1), 15–25. <http://doi.org/10.1080/09571264.2011.646254>
- Caballero, I., Blanco, C. A., & Porras, M. (2012). Iso- α -acids, bitterness and loss of beer quality during storage. *Trends in Food Science & Technology*, 26(1), 21–30. <http://doi.org/10.1016/j.tifs.2012.01.001>
- Donoghue, C., Jackson, G., Koop, J. H., & Heuven, A. J. M. (2012). *The Environmental Performance of the European Brewing Sector*. Retrieved from http://www.brewersofeurope.org/uploads/mycms-files/documents/archives/publications/2012/envi_report_2012_web.pdf
- Eissa, A. H. A., Gamaa, G. R., Gomaa, F. R., & Azam, M. M. (2012). Comparison of package cushioning materials to protect vibration damage to golden delicious apples. *International Journal of Latest Trends in Agriculture and Food Sciences*, 2(1), 36–57. <http://doi.org/10.1002/pts.760>
- Euromonitor International. (2014). What Packaging for the Challenging Beer Market to 2018? - Analyst Insight from Euromonitor International. Retrieved May 18, 2015, from <http://blog.euromonitor.com/2014/02/packaging-for-the-challenging-beer-market-to-2018.html>
- Garcia-Romeu-Martinez, M-A Singh, S. P., & Cloquell-Ballester, V.-A. (2008). Measurement and analysis of vibration levels for truck transport in Spain as a function of payload, suspension and speed. *Packaging Technology and Science*, 21(8), 439–451. <http://doi.org/10.1002/pts.798>
- Harris, C. M., Piersol, A. G. (2002). *Harris' shock and vibration handbook* (Fifth edit). New York: McGraw-Hill Companies.
- Huang, J. (2013). *Investigation of corrugated cardboard for vibration isolation*. University of Saskatchewan (Canada).
- Janssen, S., Pankoke, I., Klus, K., Schmitt, K., Stephan, U., & Wöllenstein, J. (2014). Two

- underestimated threats in food transportation: mould and acceleration. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 372(2017), 20130312. <http://doi.org/10.1098/rsta.2013.0312>
- Jarimopas, B., Singh, S. P., & Saengnil, W. (2005). Measurement and analysis of truck transport vibration levels and damage to packaged tangerines during transit. *Packaging Technology and Science*, 18(4), 179–188. <http://doi.org/10.1002/pts.687>
- Jaskula-Goiris, B., De Causmaecker, B., De Rouck, G., De Cooman, L., & Aerts, G. (2011). Detailed multivariate modeling of beer staling in commercial pale lagers. *BrewingScience*, 64(11–12), 119–139. Retrieved from <https://lirias.kuleuven.be/handle/123456789/336970>
- La Scalia, G., Aiello, G., Miceli, A., Nasca, A., Alfonzo, A., & Settanni, L. (2015). Effect of Vibration on the Quality of Strawberry Fruits Caused by Simulated Transport. *Journal of Food Process Engineering*, 39(2), 140–156. <http://doi.org/10.1111/jfpe.12207>
- Lu, F., Ishikawa, Y., Kitazawa, H., & Satake, T. (2010). Effect of vehicle speed on shock and vibration levels in truck transport. *Packaging Technology and Science*, 23(2), n/a-n/a. <http://doi.org/10.1002/pts.882>
- Maheras, S. J., Lahti, E.A., Ross, S. B. (2013). *Used Fuel Disposition Campaign - Transportation Shock and Vibration Literature Review*. Retrieved from <http://trid.trb.org/view.aspx?id=1258379#>
- Malfliet, S., Van Opstaele, F., De Clippeleer, J., Syryn, E., Goiris, K., de Cooman, L., & Aerts, G. (2008). Flavour Instability of Pale Lager Beers : Determination of Analytical Markers in Relation to Sensory Ageing. *Journal of the Institute of Brewing*, 114(2), 180–192. Retrieved from <http://onlinelibrary.wiley.com/doi/10.1002/j.2050-0416.2008.tb00324.x/abstract>
- O'Brien, M; Gentry, J P; Gibson, R. C. (1965). Vibration characteristics of fruit as related to in-transit injury. *Transactions of the ASAE*, 8(2), 241–243.
- Tabatabaekoloor, R; Hashemi, S.J.; Taghizade, G. (2013). Vibration Damage to Kiwifruits during Road Transportation. Retrieved August 26, 2015, from http://www.ripublication.com/ijafst_spl/ijafstv4n5spl_11.pdf
- Tano, K., Oulé, M. K., Doyon, G., Lencki, R. W., & Arul, J. (2007). Comparative evaluation of the effect of storage temperature fluctuation on modified atmosphere packages of selected fruit and vegetables. *Postharvest Biology and Technology*, 46(3), 212–221. <http://doi.org/10.1016/j.postharvbio.2007.05.008>
- Van Zeebroeck, M., Lombaert, G., Dintwa, E., Ramon, H., Degrande, G., & Tijskens, E. (2008). The simulation of the impact damage to fruit during the passage of a truck over a speed bump by means of the discrete element method. *Biosystems Engineering*, 101(1), 58–68. <http://doi.org/10.1016/j.biosystemseng.2008.06.003>
- Vanderhaegen, B., Neven, H., Verachttert, H., & Derdelinckx, G. (2006). The chemistry of beer aging – a critical review. *Food Chemistry*, 95(3), 357–381. <http://doi.org/10.1016/j.foodchem.2005.01.006>
- Weiskircher, R. (2008). *Summary of Prior Experiments Regarding Temperature in Sea Containers*. *CSIRO Mathematical and Information Sciences*. Retrieved from <http://wscc.scl.gatech.edu/resources/tempinseacontainers.pdf>

Zhou, R., Su, S., Yan, L., & Li, Y. (2007). Effect of transport vibration levels on mechanical damage and physiological responses of Huanghua pears (*Pyrus pyrifolia* Nakai, cv. Huanghua). *Postharvest Biology and Technology*, 46(1), 20–28.
<http://doi.org/10.1016/j.postharvbio.2007.04.006>